

Fuel Property Effects on T700 Exhaust Particulates

INTERIM REPORT TFLRF No. 373

by

Clifford A. Moses

**U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI®)
Southwest Research Institute®
San Antonio, TX 78238**

Under Contract to

**U.S. Army TARDEC
Force Projection Technologies
Warren, MI 48397-5000**

for

**Naval Air Systems Command
Fuels & Lubricants, AIR-4.4.5
PSEF, Building 2360
22229 Elmer Road, Unit 4
Patuxent River, MD 20670-1534**

SwRI Project No. 08.03227.18

TARDEC Contract No. DAAE-07-99-C-L053

June 2004

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Approved by:



Edwin C. Owens, Director
U.S. Army TARDEC Fuels and Lubricants
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14. ABSTRACT <p>T700 engine and combustor-rig tests were conducted to evaluate fuel and additive effects on exhaust particulates. Six base fuels were used ranging from a zero-aromatics synthetic fuel to diesel fuel. The effect of copper contamination on particulates was evaluated as was the effect of the additive Spec•Aid 8Q462, which has been shown to reduce particulates in some other testing.</p> <p>Particulates were characterized by both mass and size distribution. Particulate mass correlated equally well with the fuel aromatic content, hydrogen content, and smoke point. More importantly, in the engine tests, an excellent correlation was found between the particulate mass on the filters and the integrated particulate volume calculated from the particulate-size distribution. The presence of copper contamination did not affect the concentration or size of particulates. Limited results on two fuels without replication showed a 10 to 15% reduction in particulates at the cruise condition with the 8Q462 additive.</p> <p>The results indicate that a zero-aromatics fuel will reduce particulate mass about 25% compared to an average JP-5. Alternately, F-76 diesel fuel would be expected to double the particulate mass.</p>					
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EXECUTIVE SUMMARY

A combination of engine tests and combustor tests has been used to study fuel effects on exhaust particulates from the T700 gas turbine engine. The engine tests were conducted at the US Navy Air Warfare Center Aircraft Division, Patuxent River, MD. Personnel from the NASA Glenn Research Center in Cleveland, OH were responsible for the exhaust probes and sampling system as well as the analyses of gaseous emissions and particulate size distribution. Personnel from the US Army TARDEC Fuels and Lubricants Research Facility (TFLRF) were responsible for collecting and analyzing filter samples of particulates to evaluate fuel effects on particulate mass. Six base fuels were used in the test ranging from a zero-aromatics synthetic fuel to diesel fuel. The effect of copper contamination and a fuel additive were also evaluated.

In the engine tests, particulate mass correlated equally well with the bulk fuel properties of aromatic content, hydrogen content, and smoke point. More importantly, an excellent correlation was found between the particulate mass on the filters and the integrated particulate volume calculated from the particulate-size distribution data taken by NASA. On average, the combustor tests showed the same effects. The results verified that using fuels of lower aromatic content, i.e., higher hydrogen content, would reduce exhaust particulates. It is expected that using a fuel with zero aromatics will reduce particulate mass about 25% based on an average JP-5 of 17.0 vol% aromatics, i.e., 13.9 wt% hydrogen. Alternately, using diesel fuel would be expected to double the particulate mass.

Copper contamination at the 450 ppb level did not appear to increase particulate mass in the combustor tests. Filter data was not taken during the engine tests to evaluate the effect of copper contamination; however, the particle-size distribution data taken by NASA should be valid for drawing conclusions.

Limited data from the engine tests indicated that at a concentration of 256 mg/L the additive Spec•Aid 8Q462 resulted in a reduction of particulates at the “cruise” condition. This reduction was higher for the diesel fuel than the jet fuel, 15% and 10% respectively. At the concentration used in the engine tests, the additive did not reduce the particulates from the diesel fuel to the level of the jet

fuels. The effect of higher concentrations was not evaluated in the engine tests, but in the combustor tests, some reduction was noted as the concentration was increased to 1024 mg/L.

On average the results from the combustor tests supported the results of the engine test with respect to effects of operating condition and fuel, but the scatter in the data was greater than the potential effects of the copper contamination and the additive making quantitative assessments very tenuous. Copper contamination did not appear to cause an increase in particulates. There did appear to be a decrease in particulate concentration with increasing additive concentration, but if valid, it was small compared to the increase in additive concentration.

Normally combustor tests should provide a cheaper means to study fuel effects on exhaust particulates than engine testing. The advantages include:

- Lower fuel flow consumption
- Known fuel and airflow conditions
- The ability to stay on condition at high power for extended lengths of time

FOREWORD/ACKNOWLEDGMENTS

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1. INTRODUCTION

This report covers two series of tests to investigate fuel effects on gas turbine exhaust particulates.

The first series of tests were conducted jointly by the Navy, NASA, and the Army TARDEC Fuels and Lubricants Research Facility (TFLRF) using a General Electric T700 engine at the Navy Air Warfare Center Aircraft Division (NAWCAD) at Patuxent River, MD. Personnel from the NASA Glen Research Center in Cleveland, Ohio, were responsible for the exhaust probes and sampling system as well as the analyses of gaseous emissions and particulate size distribution. TFLRF was responsible for collecting and analyzing samples of particulates and polycyclic aromatic hydrocarbons (PAH). For this series of tests, this report covers only the collection of the exhaust particulates for mass determination. NASA reports the analyses of the gaseous emissions and particle size distributions in a separate report. The collection and speciation of PAH were funded by NASA under separate contract and have been reported separately.

Subsequent to the engine test, the same fuels were tested in a T700 combustor rig operated at the same conditions for airflow and fuel flow. These tests were conducted at the TFLRF turbine combustor laboratory at Southwest Research Institute in San Antonio, TX. In this series of tests, the gaseous emissions, particulate mass, and particulate size distribution were conducted by TFLRF.

GE Water Technologies provided partial support for both series of tests.

2. OBJECTIVE

The primary objective of this program was to determine the effect of fuel properties and an additive on exhaust particulates from a gas turbine. A secondary objective was to evaluate the use of a combustor rig to meet this same objective.

3. SCOPE

3.1 Test Fuels

Six fuels were used to evaluate the effects of fuel properties: five jet fuels and one diesel fuel. These fuels were selected for the following considerations:

- To vary aromatic and sulfur content
- To look at the effect of copper contamination such as commonly found on shipboard
- To determine the effect of burning diesel fuel in emergency situations

In addition, four of the fuels were tested with and without the additive Spec-Aid 8Q462, manufactured by GE Water Technologies, to evaluate this additive for soot reduction; there is anecdotal evidence that this additive reduces soot formation in gas turbine combustion.

The basic fuel matrix is provided in Table 1 with the fuel properties most related to particulates in addition to copper and sulfur content.

Table 1. Fuel Matrix						
Test Fuel	Additive evaluation?	Aromatics vol%	Hydrogen Content, wt%	Smoke Point, mm	Sulfur wt%	Copper ppm
1. JP-5 base fuel	Yes	19.8	13.9	24.0	0.117	N.D.*
2. JP-5 + copper	Yes	19.8	13.9	22.0	0.114	0.45
3. JP-5 high aromatic	Yes	24.3	13.7	21.0	0.102	N.D.
4. Synthetic A	No	0	15.5	26.6	< 0.015	N.D.
5. Synthetic B	No	14.3	14.4	35.0	< 0.015	N.D.
6. F-76	Yes	36.2	13.2	15.0	0.485	N.D.
* N.D. – not detectable by ASTM D 6732, atomic absorption						

Fuel #3 was blended by adding a commercial aromatic solvent, Hi Sol 15, to fuel #1; this solvent contains mixed single-ring aromatics that are in the jet fuel boiling range.

Two synthetic kerosenes from Fisher-Tropsch (F-T) processes were included in the matrix. The fuel designated as Synthetic A was a kerosene cut from the Shell Middle Distillate Synthesis (SMDS) process that uses natural gas as the primary resource. This fuel contains no aromatics or sulfur and

was used to represent a gas-to-liquid (GTL) kerosene. The other synthetic fuel came from the F-T process developed by Sasol in South Africa. While this fuel also contains no sulfur, it was blended from synthetic distillate streams that do contain aromatics.

A complete analysis of these fuels as conducted by the Navy is provided in Appendix A.

3.2 Test Conditions

The engine and combustor tests were conducted at three power conditions corresponding to idle, cruise, and take-off. These are considered the most important from the standpoint of exhaust emissions. Particulate and gaseous emissions at idle and take-off affect air quality in and around the flight line. On the other hand, aircraft spend most of their time at cruise, and any exhaust particulates would be injected into the upper atmosphere where they potentially increase contrails and cloud formation. Because helicopters don't have a cruise condition in the sense that fixed-wing aircraft do, the operating condition used was that of "max continuous power".

It was not possible to operate the engine at maximum rated power long enough to collect filter samples for particulates; therefore, these samples were collected only at the idle and "cruise" conditions. At the maximum rated power condition, only gaseous emissions and particulate size distribution were analyzed.

For each test fuel, three exhaust samples were collected at each power condition. The power was varied according to the sequence illustrated in Figure 1 to allow for each combination of power transition.

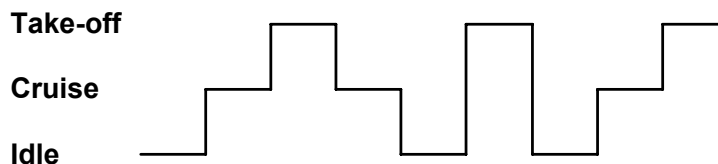


Figure 1. Test Cycle for Engine Power

At the beginning and end of each test sequence, the engine was operated on the base JP-5 fuel at the “cruise” condition to provide a baseline for hourly and daily variations in operating conditions. Gaseous emissions and particle size distribution were determined each time; particulate mass was not.

4. PHASE I: T700 ENGINE TESTS

4.1 Particulate Sample Flow System

Figure 2 illustrates the flow system for collecting particulate and PAH samples as integrated into the NASA exhaust sample collection system. A 4-port crossover valve was used to switch the sample flow between the NASA analyzers and the TFLRF particulate sample system. The exhaust sample probes and the sample line up to the crossover valve were the responsibility of NASA.

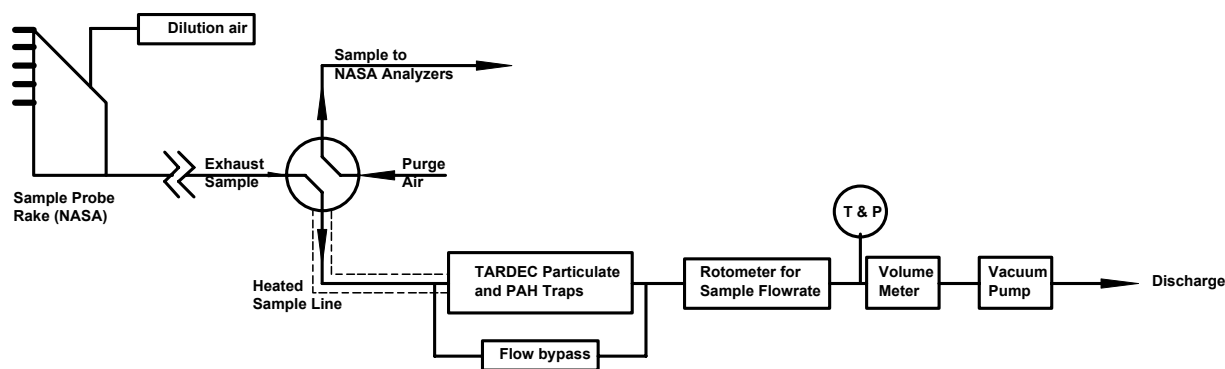


Figure 2. Flow System for Collecting Particulate Samples

A heated sample line just prior to the particulate filter housing was used to maintain a constant temperature for all the samples. The nominal sample temperature was $150 \pm 5^\circ\text{F}$.

A photograph of the particulate filters and PAH trap are provided in Figure 3. Two particulate filters are located in series within the housing, supported on stainless steel screens. The particulate filters were Pallflex fluorocarbon-coated glass fiber. These filters are rated to have a collection efficiency of >99 percent for particles above $0.5 \mu\text{m}$. Using two filters in series increases the collection efficiency. The overall diameter of the filters was 2.75 inches; the collection surface was 2.50

inches in diameter or 4.91 in² in area. The two filters were weighed together before and after the test to obtain the particulate mass. Mass was reported to the nearest microgram. The two filters together weigh about 260 mg, and the deposit weights were in the range of 0.25 to 5.5 mg.

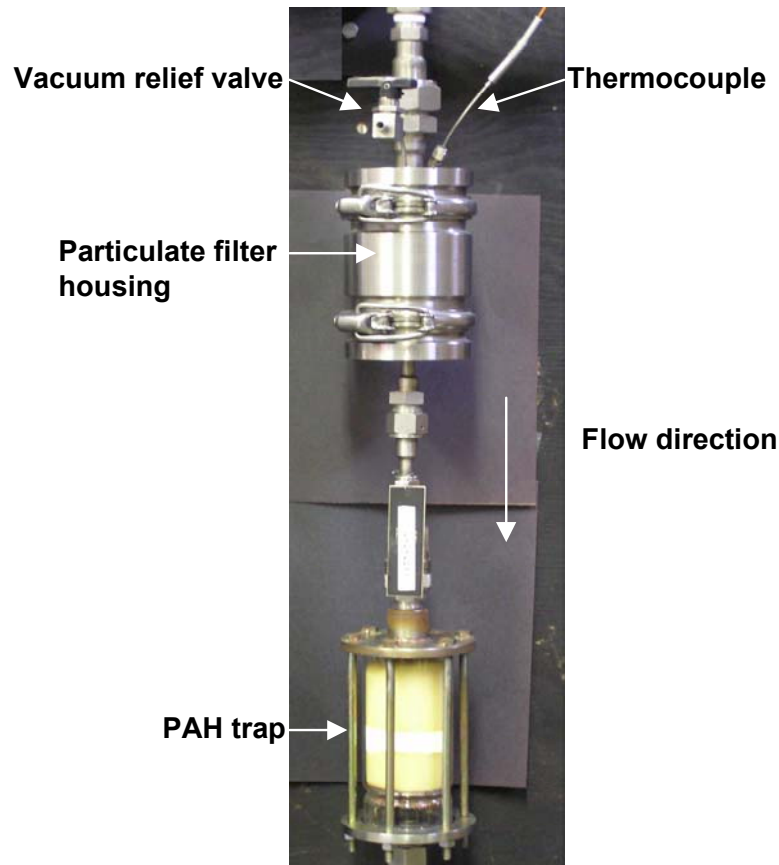


Figure 3. Particulate Filter Holder and PAH Trap

A dry gas meter was used on the particulate mass sample line to measure the volume of sample passing through the filters. A digital counter kept track of the number of revolutions of the gas meter; each revolution was 0.1 liters or 0.00353 ft³. The sample sizes were in the range of 15 to 20 ft³; the larger sample volumes were used for the idle condition and for the fuels less prone to forming soot. Sample flow rates were typically in the range of 40 to 45 ft³/hr. This was less than the flow rate generally used in the combustor lab of 100 ft³/hr, but the flow rate was limited by the size of the orifice in the sample probe. At a flow rate of 40 ft³/hr, the flow velocity through the filter was 0.33 ft/s.

The pressure and temperature of the flow were measured at the entrance to the dry gas meter to correct to standard conditions. Typically the temperature was 85 to 90°F and the pressure was 1 ± 0.1 inch of water below atmospheric pressure, or 0.036 psig, so the corrections were very small.

4.2 Procedure

It was not possible for NASA to take particulate samples for size analysis at the same time the filter samples were being taken by TFLRF. Therefore, immediately before the filter sample was to be taken, a sample was taken by the NASA system and analyzed for gaseous emissions and particulate size distribution; both analyses were done in duplicate. The dilution ratio was also determined. During this time, purge air was flowing through the sample line to the TFLRF filter rig; this purge air bypassed the filter, but flowed through the rotameter, dry gas meter, and vacuum pump so that they could continue running and prevent the formation of a transient at the beginning of the filtration.

Immediately following the NASA analysis, the sample flow was directed to the bypass around the TFLRF system. When the flow was stabilized and brought to temperature, the downstream valve was first opened to connect the filter system to the vacuum pump and then the upstream valve was opened to allow the exhaust sample to flow through the filter system. When the sampling period was finished, the upstream valve was first closed and then the downstream valve. A small needle valve on the particulate filter housing was then opened to bring the pressure to atmospheric pressure so the housing could be opened and the filters removed.

The two filters were handled with tweezers when placed in the filter housing and when removed so that no oils or dirt would be transferred from the fingers. When the filters were removed, they were placed back in their plastic covered container, sealed, and put in cold storage.

The pre-test and post-test weighings of the filters took place at Southwest Research Institute in San Antonio, TX. Prior to both the pre-test and post-test weighings, the filters were conditioned in accordance with CFR 40 Part 86.112. The specific conditions at SwRI are $21 \pm 1^\circ\text{C}$ with a dew point of $9.5 \pm 1^\circ\text{C}$. The filters were isolated in pairs in plastic containers for shipping. The filters were

shipped back to TFLRF/SwRI in a picnic-type cooler that contained a styrofoam box filled with dry ice to keep the cooler chilled during transit. This precaution was taken so that any organic material on the filters would not evaporate.

4.3 Analysis and Results

The analysis of particulate mass (PM) data was in several steps. First it was necessary to account for variations in engine operation between tests. This is done by normalizing the results to the fuel flow rate as an emissions index for particulate mass, EI (PM), expressed in terms of grams of carbon per kilogram of fuel. Then daily variations in temperature and humidity were accounted for based upon the results with the reference tests that were conducted with the JP-5 baseline fuel before and after each series of tests. Finally, the EI (PM) results were related to the fuel variables to directly address the objective.

4.3.1 Engine Variations

Normalizing the PM to the fuel flow is not as straightforward as it might seem. The fuel flow rate was measured during each test, but the particulate mass was taken from only a small sample of the exhaust stream. First it is necessary to determine the PM concentration per unit volume of exhaust and then use the fuel-air ratio to determine the PM concentration per unit volume of fuel. Fuel-air ratio must be determined from the exhaust emissions; the following function was used to calculate the fuel-air ratio, FAR:

$$FAR = \frac{B \times [f(CO_2) + f(CO) + f(HC)]}{f(O_2) + f(CO_2) + f(NO_2) + \{f(CO) + f(NO) + C \times [f(CO_2) + f(CO)]\}}$$

$$\text{where } B = 0.21 \times \frac{\text{synthetic molecular wt. of fuel}}{\text{molecular wt. of air}}$$

$$\text{and } C = \frac{(H/C)_{wt.}}{0.168}$$

The constants B and C allow variations in fuel composition to be taken into account, but for this work, the difference was less than 1 percent.

4.3.2 Ambient Variations

Daily variations were evaluated using the particle size distribution data developed by NASA. These data were taken three times each day:

- In the morning before the first test
- Mid-day during the change of test fuels
- At the end of the day

The fuel was the baseline JP-5, and the engine was operated at the “cruise” condition.

It was necessary to use the NASA particle size distribution data for this evaluation since that data was taken for all tests whereas the particulate filters were only employed for single tests on each fuel at idle and “cruise”. The use of these variations in evaluating the particulate mass data was a valid approach because, as will be shown in Section 5.4, there was a very good correlation between the particulate mass from the filters and the particulate volume calculated from the particle size distribution data. Figure 4 shows the variation in particulate volume concentration for the base fuel during each of the five days of testing. The real reasons for these variations is not known but are assumed to be related to changes in temperature and humidity. On days 1 and 2 there was a consistent increase in emissions as the day progressed; day 5 showed the same rate of increase but starting from a lower level. Day 3 was unique because there were severe thunderstorms and heavy rain in the area all day.

The correlations through these data were used to adjust the particulates data of Figure 4 to a common base line. The results are presented in Figure 5; with these factors applied, the correlations for each set of daily data are the same horizontal line.

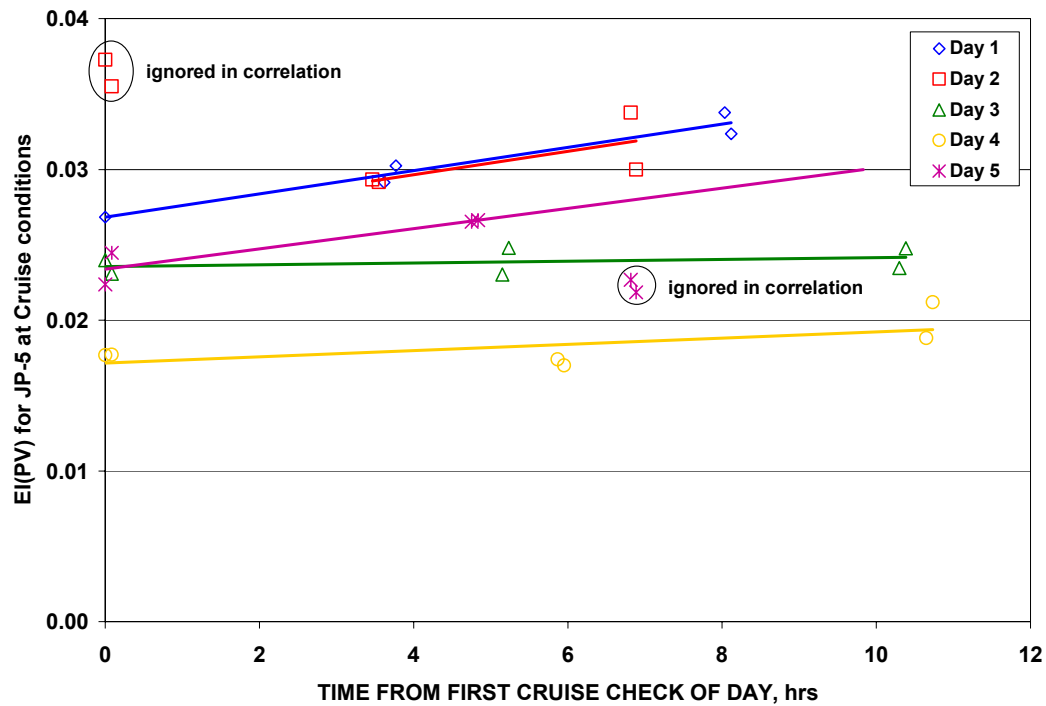


Figure 4. Variation in Exhaust Particulate Concentration with Base JP-5 at “Cruise” (Max Continuous Power) Condition

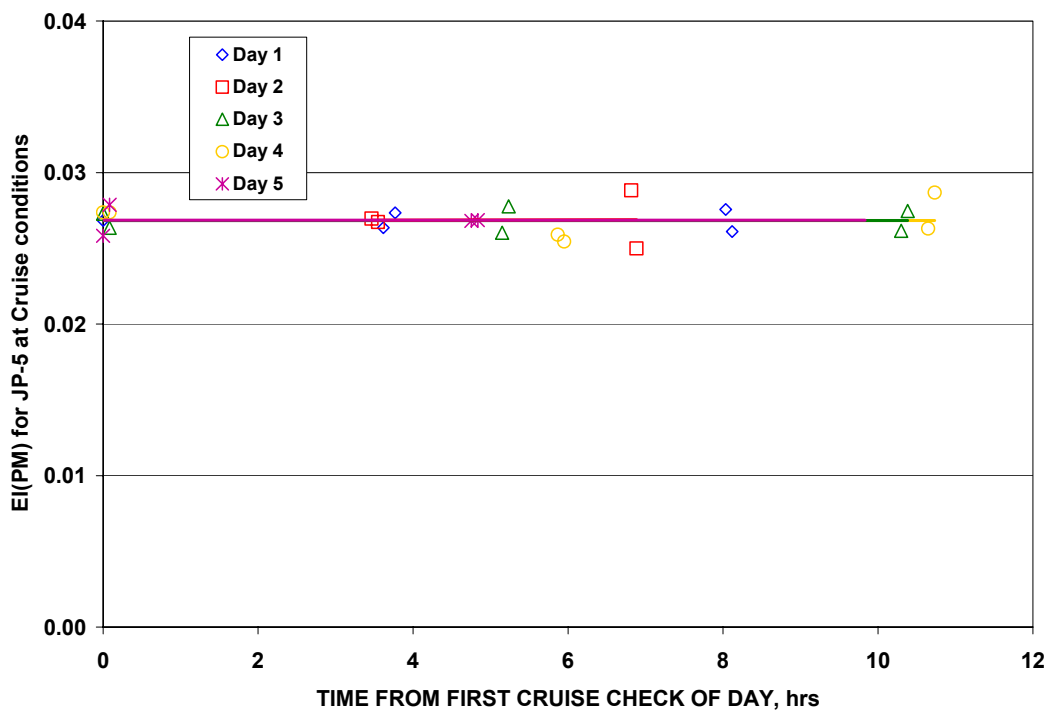


Figure 5. Exhaust Particulate Concentration with JP-5 Base Fuel Adjusted for Daily Variations

In the analyses below, this correction was applied only to the particulate mass data taken at the “cruise” condition. It is not known whether this correlation would be valid for the idle data so no correction was made.

4.3.3 Fuel/Additive Effects on Particulates

Filter samples for particulate mass were not taken for the fuels contaminated with copper; this was the decision of the Navy personnel in charge of the test. Filter samples were taken for all of the other fuels. Three filter samples were taken for the base JP-5 at both idle and “cruise” conditions in a futile attempt to evaluate reproducibility. Unfortunately, two of each of them were not good samples due to teething problems since there was not time allowed for shakedown testing. The reasons for this will be addressed later in the section on Problems.

The fuel effects on particulate concentration are summarized in Figure 6 using the hydrogen content of the fuel as a correlating parameter. As expected, significantly more particulates were generated at the higher power condition. At both power conditions there is the expected increase in particulate concentration for fuels with lower hydrogen content. Figures 7 and 8 correlate the same data with aromatic content and smoke number. The correlation models for all three correlations are exponential, and all have r^2 greater than 0.95 indicating that all three are equally good predictors of combustion quality including the diesel fuel and the synthetic fuels. It should be noted that the presence of the additive did not affect the value of the smoke point for any of the fuels.

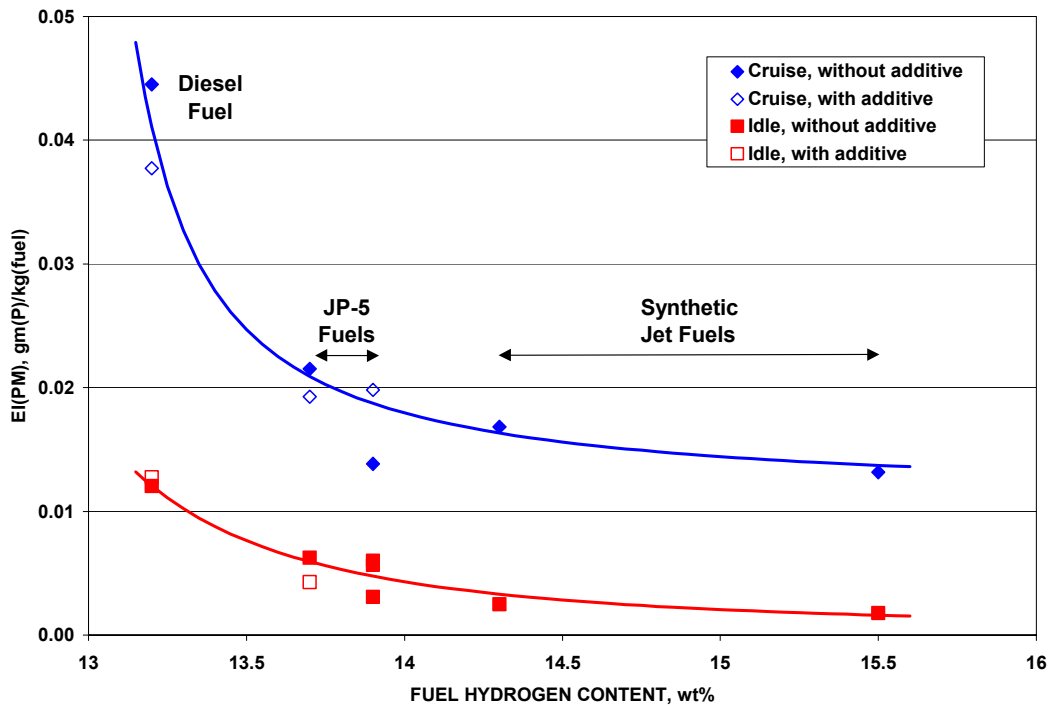


Figure 6. Correlation of Particulate Concentration with Fuel Hydrogen Content

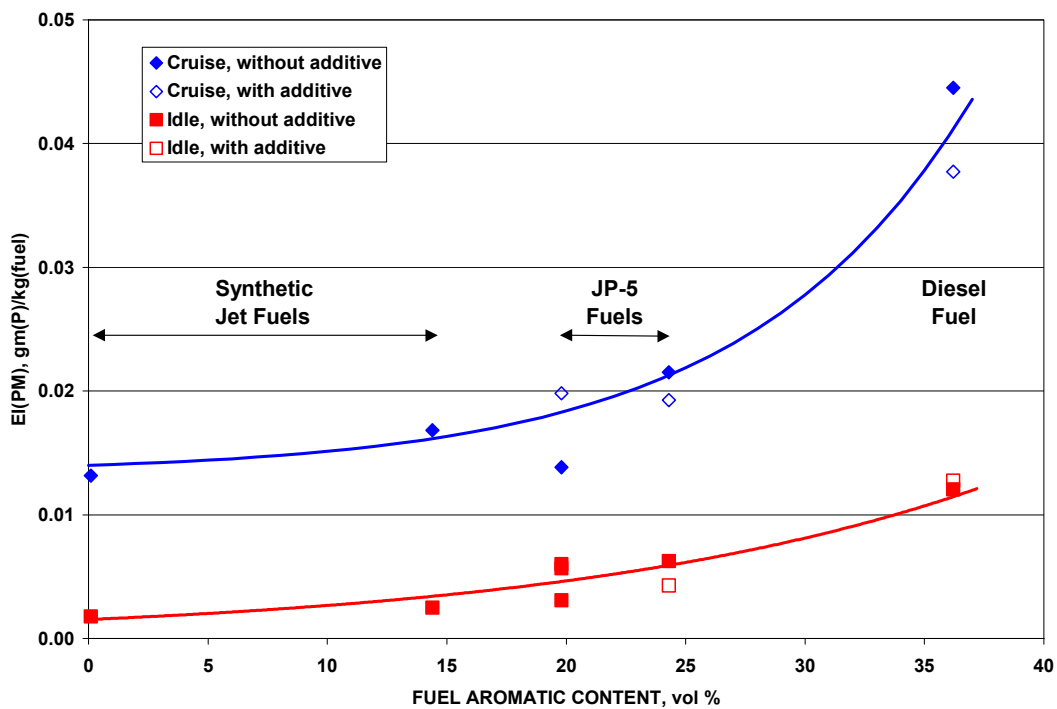


Figure 7. Correlation of Particulate Concentration with Aromatic Content

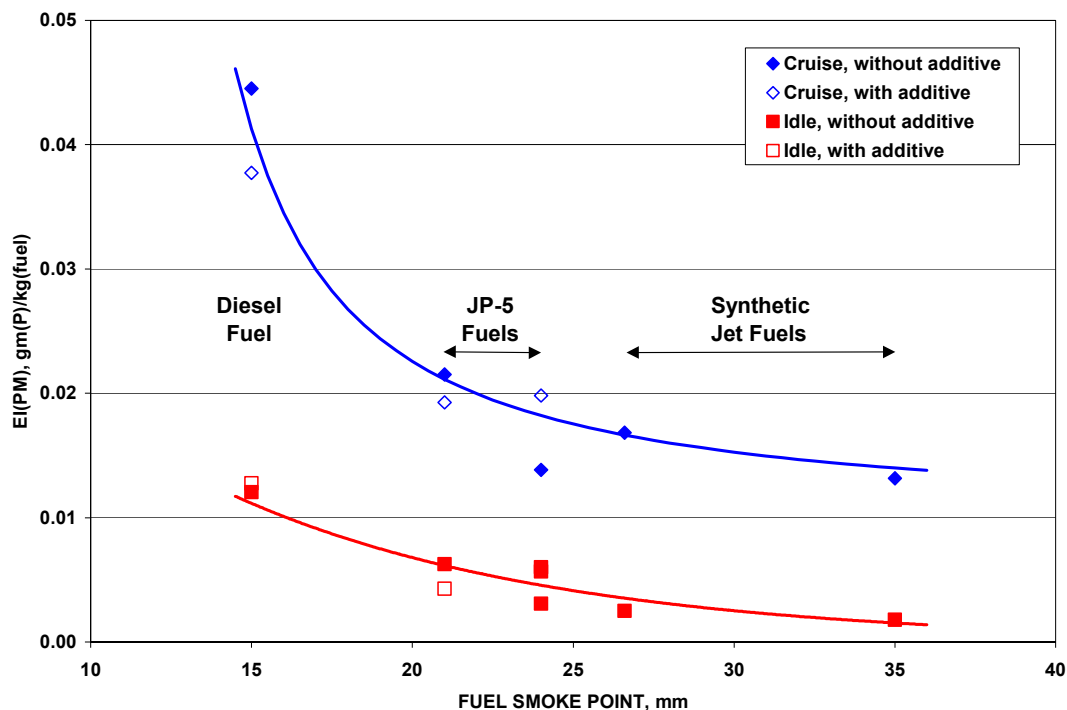


Figure 8. Correlation of Particulate Concentration with Smoke Point

According to the PQIS report for 2002 (ref 1), the hydrogen content of most JP-5 lies between 13.4 and 14.4 wt%, with a mean of 13.9 wt%. Using the correlation of Figure 6, the variation in EI (PM) in T700 exhaust would be expected to be in the range of 0.016 to 0.028 with a mean of 0.019 gm(C)/kg (fuel).

The results show that using a fuel with no aromatics will reduce exhaust particulates. At the Max continuous power condition, the reduction would be in the range of 15 to 50% depending on the JP-5 used for comparison. Base on a mean JP-5, an average reduction of about 25% could be expected. Alternately, using F-76 could be expected to result in a 100% increase in particulates based on the mean JP-5. This estimate is based on data at the max continuous power condition only. The effects could be different at other power conditions.

At the “cruise” condition, an evaluation of the additive for reducing particulates is only possible for two of the fuels and there were no replicates. The limited results indicated a 10% reduction for the high-aromatic fuel and a 15% reduction for the diesel fuel. Directionally, these reductions are in

agreement with a previous series of combustor tests in which a greater reduction was realized for a fuel with higher aromatic content. (Ref 2)

The results are inconclusive at the idle condition, but particulates are less of an issue at idle.

4.4 Comparison with NASA Particulates Data

The particle size distributions determined by NASA can be integrated to give a total particulate volume. This was done for the particle size distributions of the samples taken just prior to each of the filter samples. The results for all the fuels at both the idle and “cruise” conditions are presented in Figure 9; both mass and volume data are normalized to the same unit volume of exhaust. One would expect the particulate volume and mass to correlate, but simultaneous measurements have not been reported in the literature. Some presentations at particulate workshops have indicated a poor correlation. These data are, however, very well correlated over a broad range of particulate concentration. The slope of the correlation line is the effective density of the particulate, i.e., 1.02 gm/cm^3 .

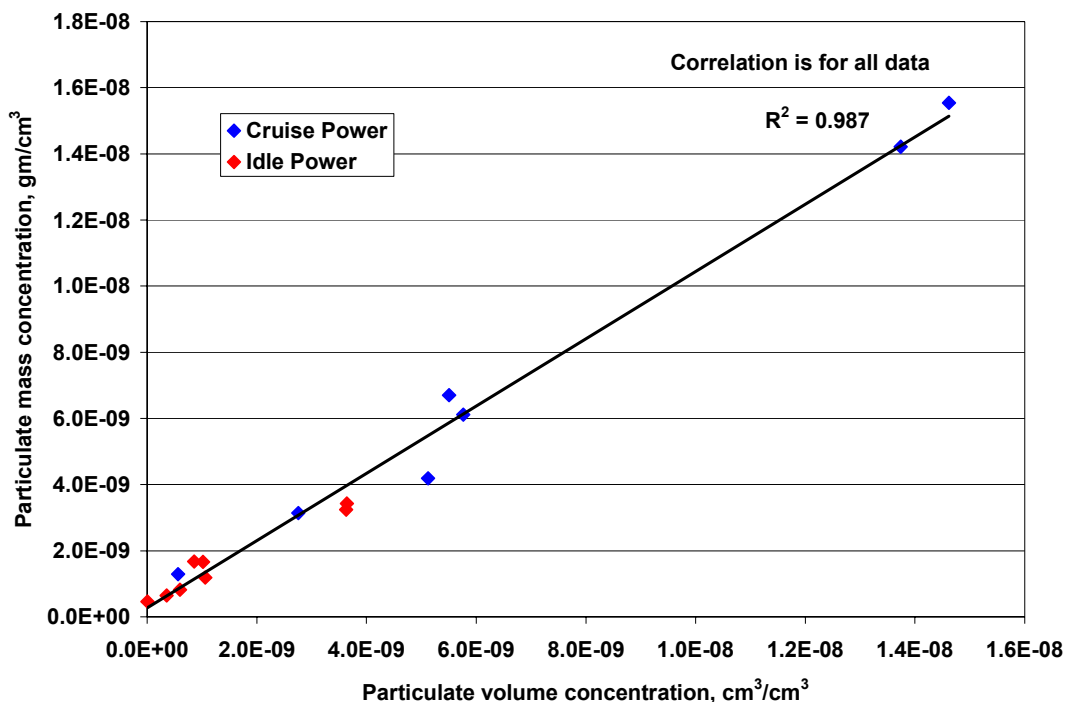


Figure 9. Comparison of Particulate Mass Concentration with Particulate Volume Concentration

4.5 Problems

Time constraints on the first day of testing prevented any shakedown tests to establish procedures and problems occurred in the first several samples.

The filter trap system had to be set up outside since there was no room in the NASA trailer and personnel were not allowed inside the test cell during engine operation. Previous use of the filter traps and flow system were inside in a controlled environment. For the initial tests, the filters were removed and replaced at the outside location. It is thought that two of the filters from these early tests were contaminated with some unknown material because the weighings were unusually heavy although the filter was not unusually black. At the end of the first day, a procedure for disconnecting the sample lines and other utilities from the particulates cart was worked out, and for the rest of the tests, the particulates cart was wheeled to an adjacent building and taken inside to remove and replace the filters from the holders.

One other early sample was negated because the valves upstream and downstream of the filter housing were opened and/or closed in the wrong order so that the filter was damaged.

The flow rate of the exhaust sample line were unknown until after the test started, and proved to be much less than the sample flow that was normally used when collecting particulate samples from the combustor. Also, the particulate concentration was unknown. These two factors made it impossible to judge how long to sample in order to obtain a significant amount of deposit on the filter, so the first samples were lighter than desired to reduce errors in weighing.

It was planned to conduct some replicate tests on the base fuel with and without the additive at the end of the week, but the team ran out of time and the testing had to be terminated after the last diesel fuel test so that some of the NASA personnel could make their airline connections home.

It was desirable to maintain a constant sample temperature to avoid variations due to condensibles. Again, without a shakedown test, the sample temperatures were not known until the first test. The

intended sample temperature was nominally 120°F, however, the first test was at 150°F, and so all subsequent tests were conducted at that sample temperature.

One these early teething problems were worked out, after the first day the tests went very smoothly except on the third day when heavy storms blew including tornadoes that were sighted within a few miles of the test facility.

4.6 Summary of Engine Tests

Other than not having an opportunity to conduct some initial shakedown tests, this phase of the project went very smoothly. The only deficiency was that the difficulties in the first tests meant that multiple valid samples were not collected on the base fuel and repeatability of particulate mass concentration could not be evaluated. Also, the evaluation of the effect of the additive was limited to only two fuels. From the standpoint of the overall program, these deficiencies were alleviated by the multiple samples of particle-size distribution made by NASA personnel; those results are reported elsewhere.

The integration with the NASA sampling system was made without difficulty and coordination of taking samples was very smooth. Due to the limited sample flow, it was not possible for NASA to take samples for analysis at the same time the filter samples were being taken. However, the engine operation was very stable and there was only a few minutes between NASA samples and the TFLRF samples. Since the NASA samples were very repeatable, it is safe to assume that the emissions data and dilution ratios provided by NASA were valid during the time of the TFLRF filter samples.

The particulate mass data was normalized to the fuel flow rate of the engine as a means of accounting for variations in engine operation. The use of a base fuel three times a day at the “cruise” condition allowed daily variations in ambient conditions to be accounted for. The resultant emissions indices for particulate mass, EI (PM), correlated equally well with the fuel parameters that are generally considered to affect or relate to soot formation during combustion, i.e., hydrogen content, aromatics, and smoke point.

Limited data indicated that the presence of the additive Spec-Aid 8Q462 did result in a reduction of particulates at the “cruise” condition. This reduction was higher for the diesel fuel than the jet fuel, 15% and 10% respectively. Getting a larger reduction with a fuel that produces more particulates was in qualitative agreement with earlier combustor tests on fuels of different aromatic content. At the test concentration, the additive did not reduce the particulates from the diesel fuel to the level of the jet fuels. The effect of higher concentrations was not evaluated.

Using a fuel with no aromatics would reduce particulates and could therefore be used to improve air quality around air bases and flight decks. The reduction in particulates for the T700 at the “cruise”, i.e., max continuous, power condition would average about 27% based on a mean JP-5. At the other extreme, using diesel fuel in the T700 would likely double the particulates in the exhaust.

Based on the correlation between the NASA and TFLRF measurements, particle size distribution shows significant promise as a quick method to determine particulate mass in the exhaust of gas turbine engines. Typically the time was about 2 minutes compared to the 20 to 60 minutes used to obtain the filter samples, depending on the engine operation condition.

5. PHASE II: T700 COMBUSTOR TESTS

5.1 T700 Combustor

The combustor rig was fabricated using the combustor liner of T700 engine. For combustor studies such as this to evaluate fuel and additive effects on emissions, it is common to use only a portion of the entire combustor to reduce costs of fabricating the test rig and to reduce fuel costs. For this study, a three-cup sector of the combustor was used as shown in Figure 10. The cooled sidewalls would not be present in a complete combustor; however, since the combustion in the center cup is effectively shielded from the cooled sidewalls by the combustion cups on either side, the combustion of the center cup is considered to be representative of an engine installation. According to the engine manufacturer, fuel changes that affect emissions in this combustor rig would be expected to produce similar results in the full engine.

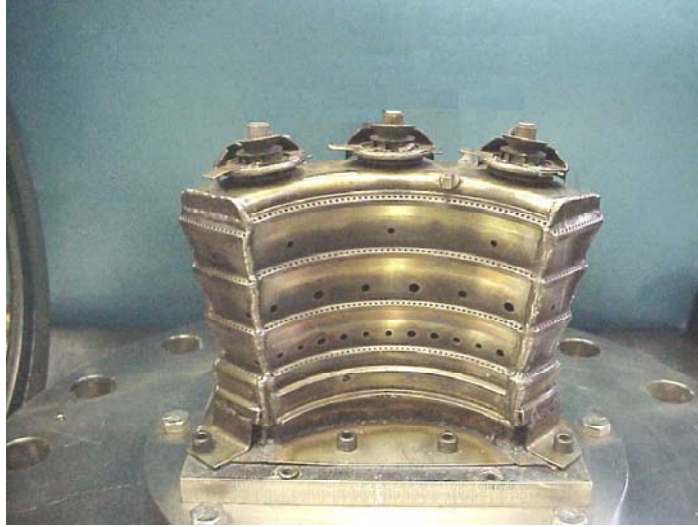


Figure 10. 3-Cup Sector Combustor Rig

The combustor was installed in a pressurized flow system as shown in Figure 11. In this picture, the flow is from left to right. The combustor is mounted to the middle flange on the right side. The fuel lines and instrumentation feed through the bosses in the center. The hoses on the right side, downstream of the flanges, provide cooling water to lower the temperature of the flow to protect the back-pressure valve. The two black hoses to the right of center connect to the emissions probe, which feeds through the middle flange on the right side. The particulates probe is located on the opposite side and is not visible in this view; it looks very similar to the emissions probe.

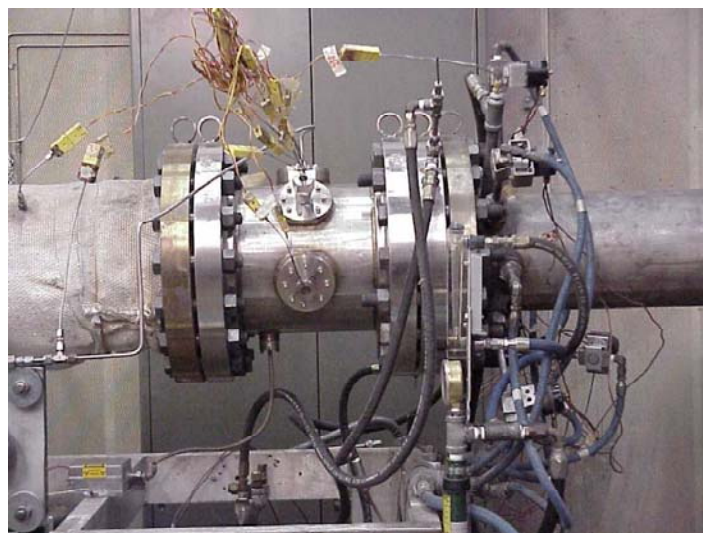


Figure 11. Pressurized Combustor Rig with Test Combustor Installed

5.2 Gaseous Exhaust Emissions

The standard gaseous exhaust emissions, consisting of CO, hydrocarbons (HC), NO_x, CO₂, and O₂, were sampled and measured in accordance with the Society of Automotive Engineers ARP-1256 “Procedure for Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines.” For the first time in this laboratory, the gas analyzers were connected to a data acquisition system for continuous monitoring. The intention was to allow for a better understanding and accounting for variations in flow parameters during the actual time that filter samples and particle size distributions were being taken. The sample and logging rate was about 0.1 Hz.

5.3 Particulate Sampling System

The particulate sample is taken at the exit of the combustor. Figure 12 is a picture of the combustor exit showing both the particulate probe (bottom) and the gaseous emissions probe (top). Figure 13 is a flow schematic of the particulate sampling system. The sample is divided into four streams for determining the following:

- Particulate mass and chemistry
- Volatile and condensed PAH
- Particulate size distribution
- Dilution ratio of particulate sample



Figure 12. Photograph Looking Through Combustor Exit Toward Fuel Injectors Showing the Sampling Probes for Particulates (top) and Gaseous Emissions (bottom)

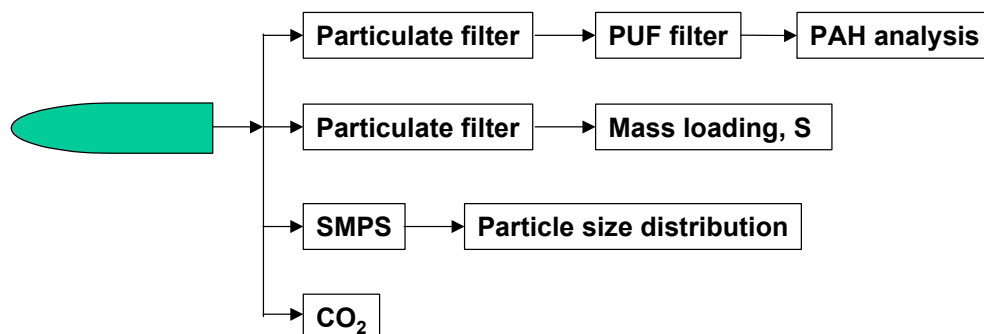


Figure 13. Flow Diagram of Particulate Sampling System

A special sampling probe was required for sampling the particulate from the combustor exhaust flow. Unlike the sample for gaseous emissions, the particulates must be diluted to prevent agglomeration and cooled to reduce migration to the wall. Furthermore, the probe must be cooled to survive in the environment of the combustor exhaust; at the most severe operating condition, i.e., Take-off, the exhaust temperature is greater than 2000°F. Figure 14 is a schematic of the probe developed for this project. The sample line runs down the centerline of the probe. A flow of chilled nitrogen flows up the annulus around the sample line. The unique aspect is that the first two inches of the sample line are fabricated from sintered stainless steel and therefore porous. When the nitrogen flow reaches the tip of the probe, it permeates through the porous wall to rapidly dilute and cool the particulate sample. The CO₂ concentration in the particulate sample line is compared to the CO₂ in the gaseous sample line to determine the dilution ratio.

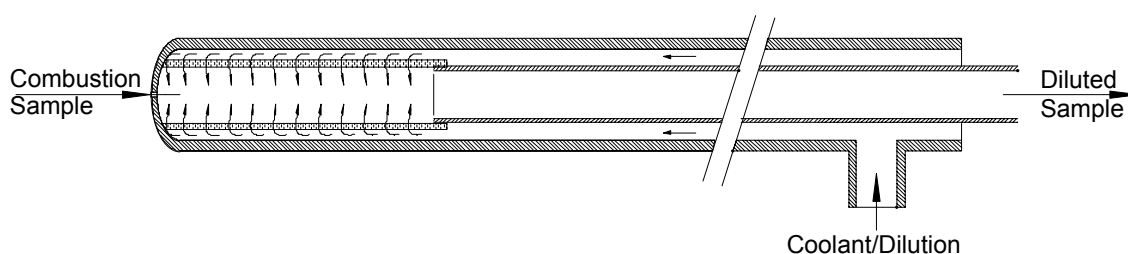


Figure 14. Schematic of Particulate Sampling Probe

The particulate filters were described earlier in Section 5.1 and a picture of the holder was provided in Figure 3. The operation was identical to that described earlier except that the sample size for the particulates was approximately 70 ft³ at idle conditions, and 45 ft³ for cruise, and 25 ft³ for takeoff.

The analysis of particle size distribution was performed using a Scanning Mobility Particle Sizer (SMPS) system, Model 3025; this is a commercial system manufactured by TSI, Inc. Within the SMPS system, the particles are sized with an Electrostatic Classifier, and the concentration of each size is measured with a Condensation Particle Counter. The system was set up to measure size distributions nominally in the 10 nm to 300 nm range. Figure 15 is an example of a particle size distribution scan. The “background” scan was taken a few minutes after the combustor was extinguished; with this low a background level, there is no question about contamination from the air or fuel.

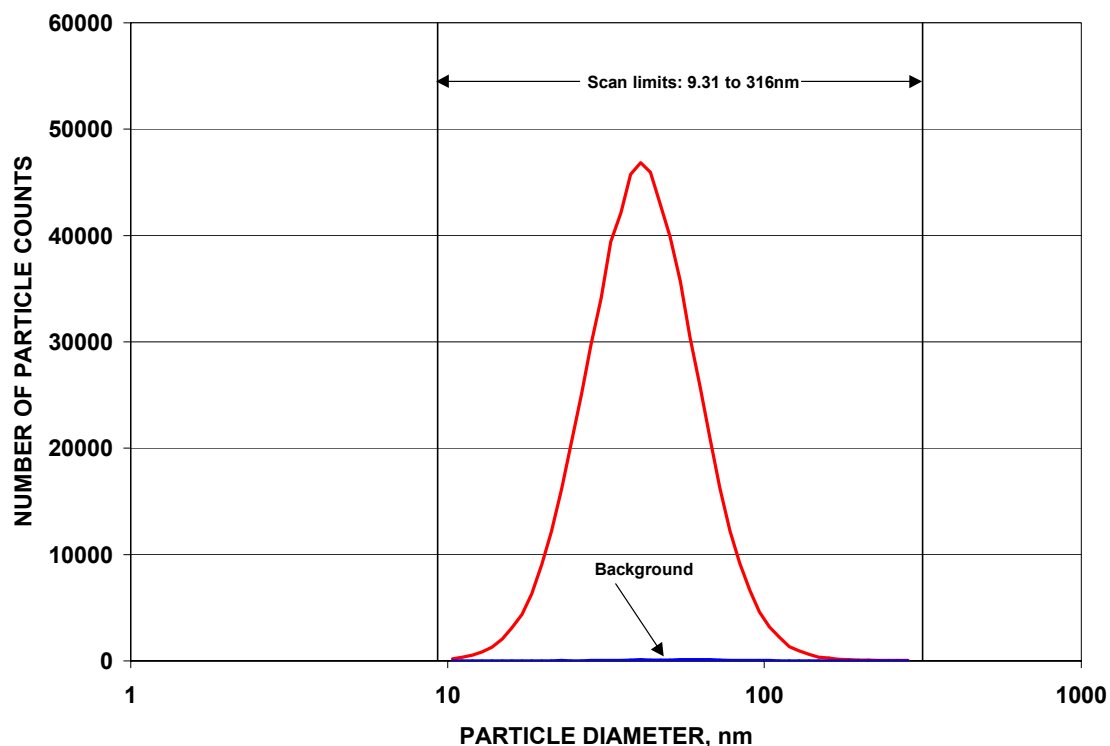


Figure 15. Example of Particle Size Distribution Scan with SMPS

5.4 Testing Procedure

The engine tests described earlier were conducted by changing the power conditions while keeping the fuel constant. This approach is time consuming when conducting combustor tests; the major time factor is the thermal inertia of the air heater. For these tests, the combustor flow conditions

were cycled sequentially. The fuels were stored in drums just outside the test cell. Fuel lines from the drums were connected to a small manifold through a series of solenoid valves. Each fuel was tested in triplicate at each of the three test conditions: idle, “cruise,” and take-off. The test sequence at each power condition is given in Table 2. The sequencing was designed to provide changes in both directions of additive concentration.

Table 2. Test Sequence at Each Power Condition	
Base Fuel	Additive Concentration mg/L
JP-5	0
	256
	256
	0
	0
JP-5 + Cu	256
	0
	0
	256
	256
JP-5 (HA)	0
	128
	256
Synthetic A	512
	0
	128
JP-5 (HA)	256
	512
	0
Synthetic A	0
	128
	256
JP-5 (HA)	512
	1024
	0
Synthetic A (GTL)	0
	256
	256
	0
	0
F-76	256
	0
	0
	256
	256
JP-5 (5-hour test)	256

The effect of additive concentration was evaluated with the high-aromatic fuel, JP-5 (HA). These variations were done in a single sequence rather than alternating as with the other fuels. On the first two days the concentrations were 128, 256, and 512 mg/L. During the third sequence, the lowest concentration was replaced with 1024 mg/L.

At the end of the matrix of fuel tests at each power condition, a five-hour test was conducted to determine if a historical effect existed.

5.5. Test Conditions

The flow conditions for the air and fuel were provided by General Electric Aircraft Engines as their best estimate based on the operating parameters from the engine tests at the Patuxent River Naval Air Station. These conditions are given in Table 3.

Table 3. Nominal T700 Combustor Operating Parameters			
Conditions	Air Pressure psia	Air Temperature °F	Fuel/Air
Idle	58	457	0.0183
Cruise	208	764	0.0228
Take-off	251	870	0.0258

5.6 Results

It was not necessary to adjust the combustor data for variations in the ambient conditions as was done for the engine data because the air flow in a combustor laboratory is measured and controlled for pressure, temperature, and flow rate as independent variables. Also, after the air is compressed, the water is removed, so there are no ambient humidity effects. The particulate mass on the filters was normalized to the fuel flow rate in the same manner as it was for the engine tests and expressed as an emissions index, EI (PM), with the units of gm (particulate)/kg (fuel).

The fuel-air ratio for the calculations was determined from the measured fuel and airflows rather than from the gaseous emissions, which was used for the engine data. In many of tests, there were variations in fuel-air ratio during the sampling time of the particulates. Because the operating and

emissions data were recorded by the computer, it was possible to determine average values during the sampling time.

Generally speaking, there was a lot of scatter in the later data at the cruise condition and the early data at the take-off condition. The root of the problem was unsteady fuel delivery from the fuel drums, which had to be stored outside, to the test cell. This caused fluctuations in the fuel-air ratio and seems to have manifested itself in low CO₂ readings. Both were important to this testing because particulate formation is sensitive to fuel-air ratio and the CO₂ level is used to calculate the dilution ratio in the particulates probe. This will be discussed further in Section 5.9 Problems.

5.6.1 Effects of Fuel and Power Condition

Figure 16 summarizes the data for particulate mass for the test fuels at each of the power conditions. The bar graphs are the average of the data, and the error bars show the maximum and minimum values of the three data at each matrix point. As expected the particulate levels increase with power condition. The gas-to-liquid (GTL) fuel with zero-aromatic (earlier called “Synthetic A”) burned much cleaner than the conventional jet fuels, while the F-76 diesel fuel produced much higher particulates. Within the data scatter, the copper contamination does not appear to increase the particulates.

Figure 16. Summary of Fuel Effects on Particulate Emissions at Idle, Cruise, and Take-Off

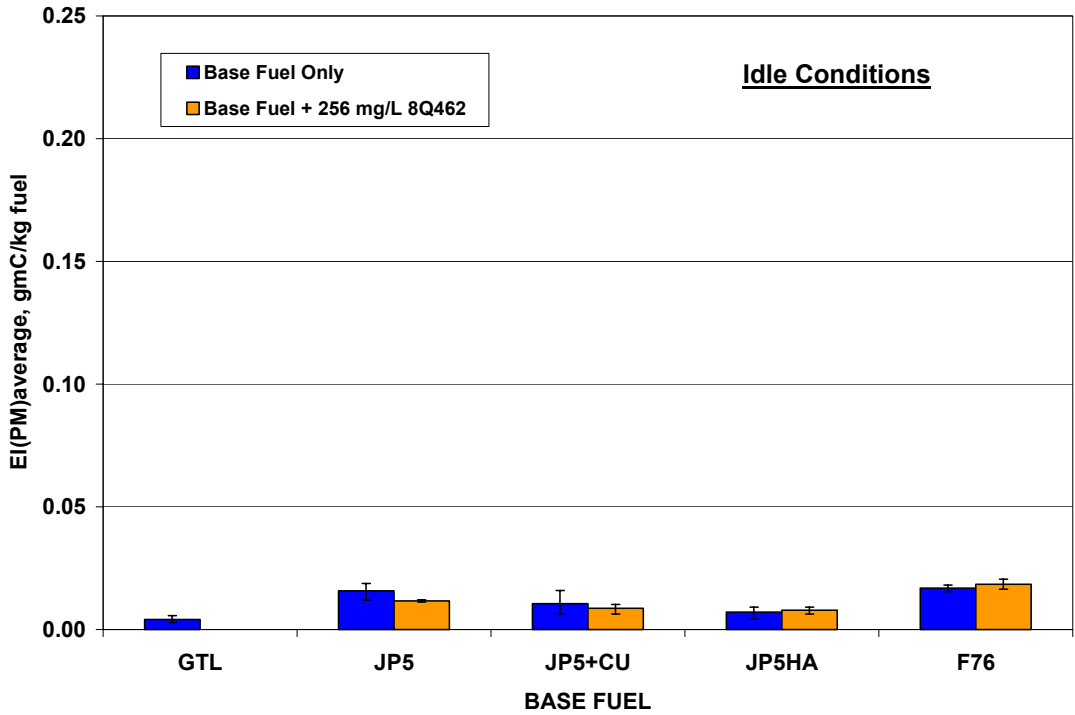


Figure 16a

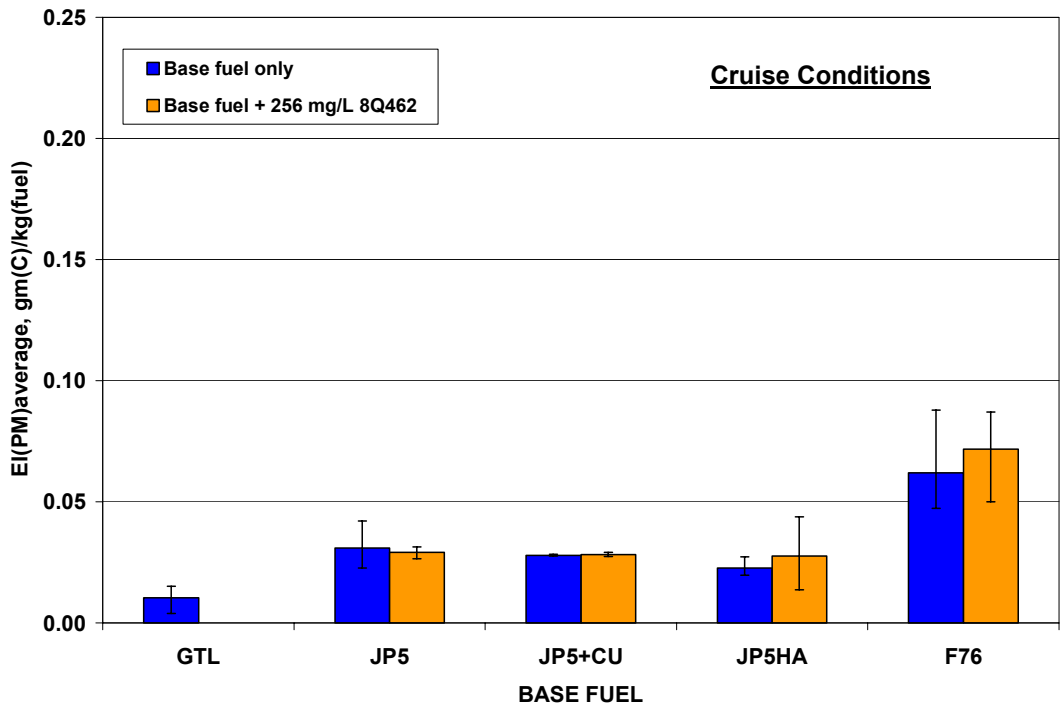


Figure 16b

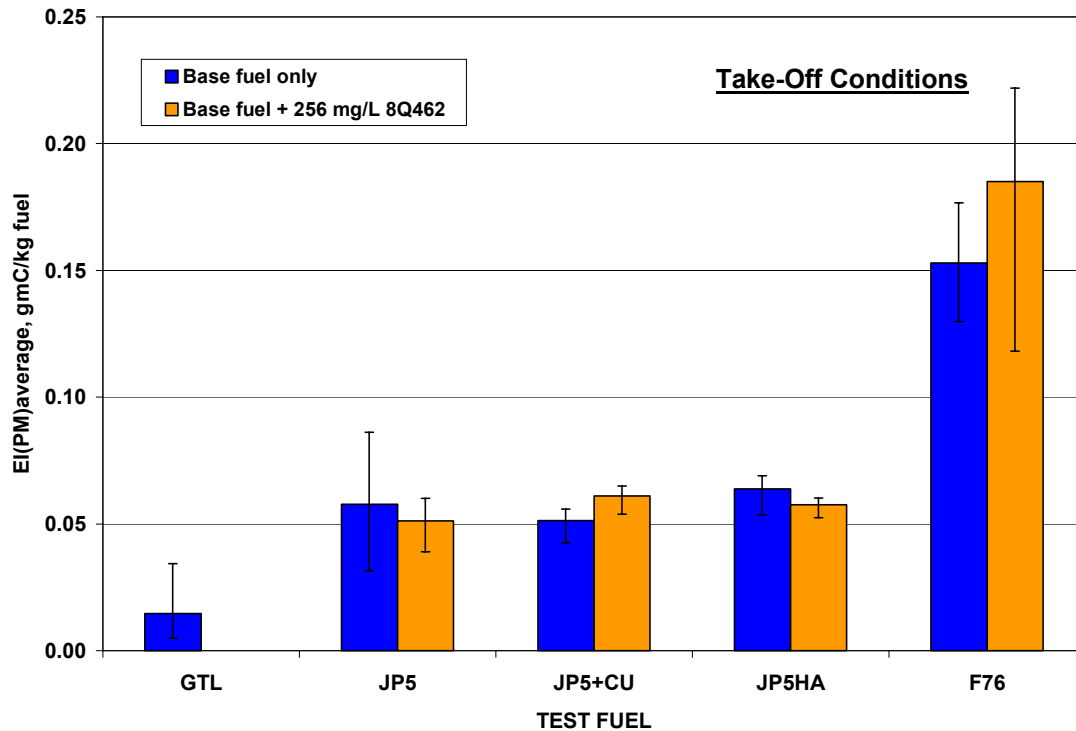


Figure 16c

For the data on “fuel with additive,” only the data for 256 mg/L of additive are shown to avoid confusion with concentration effects. Unfortunately, the scatter in the data is greater than the potential effect of the additive as seen in the engine testing so any potential effect is obscured.

Figure 17 presents a correlation of the results of the base fuels without additive with the hydrogen content of the fuel; this corresponds to Figure 6 for the engine tests. Each correlation is exponential. The effect of power condition is very similar between the combustor and the engine. From Figure 6, the particulates at the cruise condition were about four times as great as the particulates at idle condition. For the combustor tests, the correlation for the cruise condition is between three and four times the level of the idle correlation. This is very close considering the scatter in the combustor data.

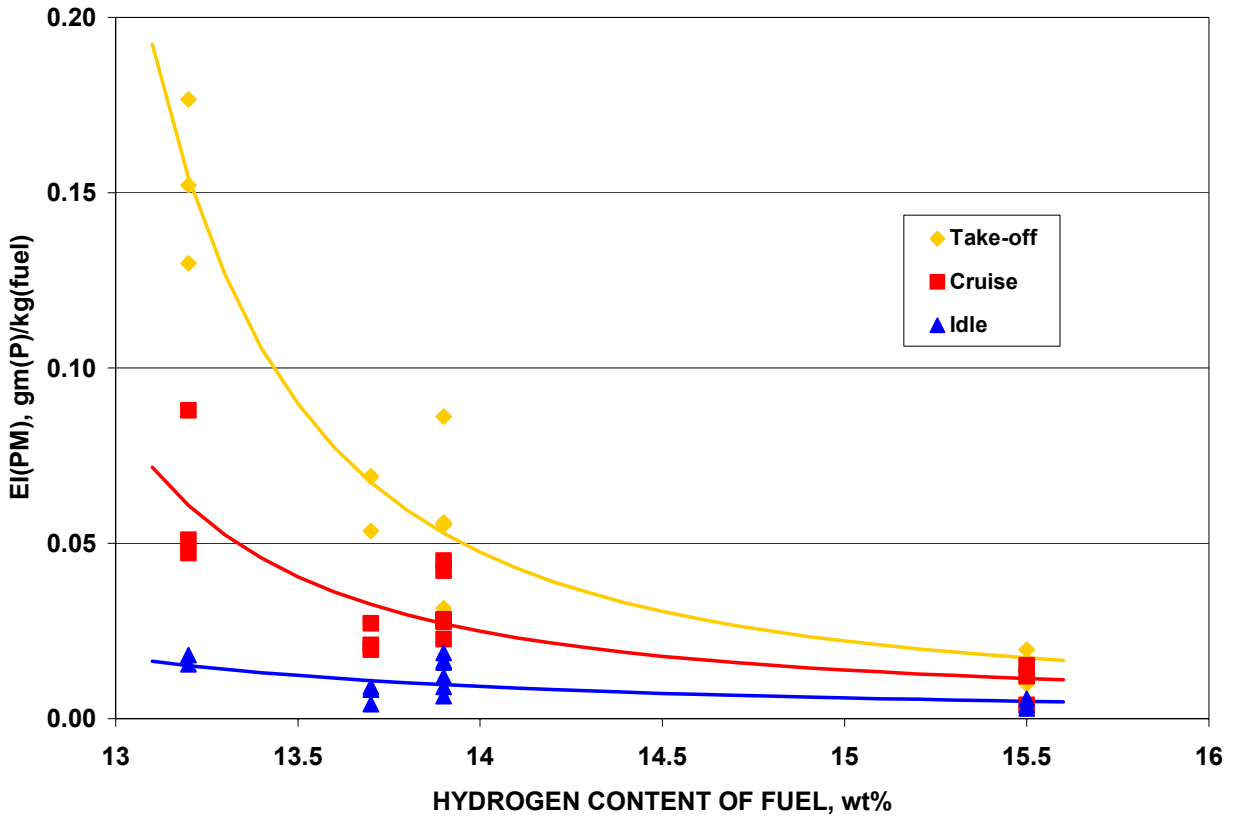


Figure 17. Correlation of Particulate Concentration with Fuel Hydrogen Content for Fuels Without Additives

5.6.2 Additive Concentration Effects

Figure 18 presents the results from the combustor tests with varying additive concentration. The idle data was the most consistent during all of the testing, but conclusions on particulates at idle are very dubious because they are very low. Taken as a whole, the data at cruise and take-off contain too much scatter because of the flow instabilities to draw conclusions.

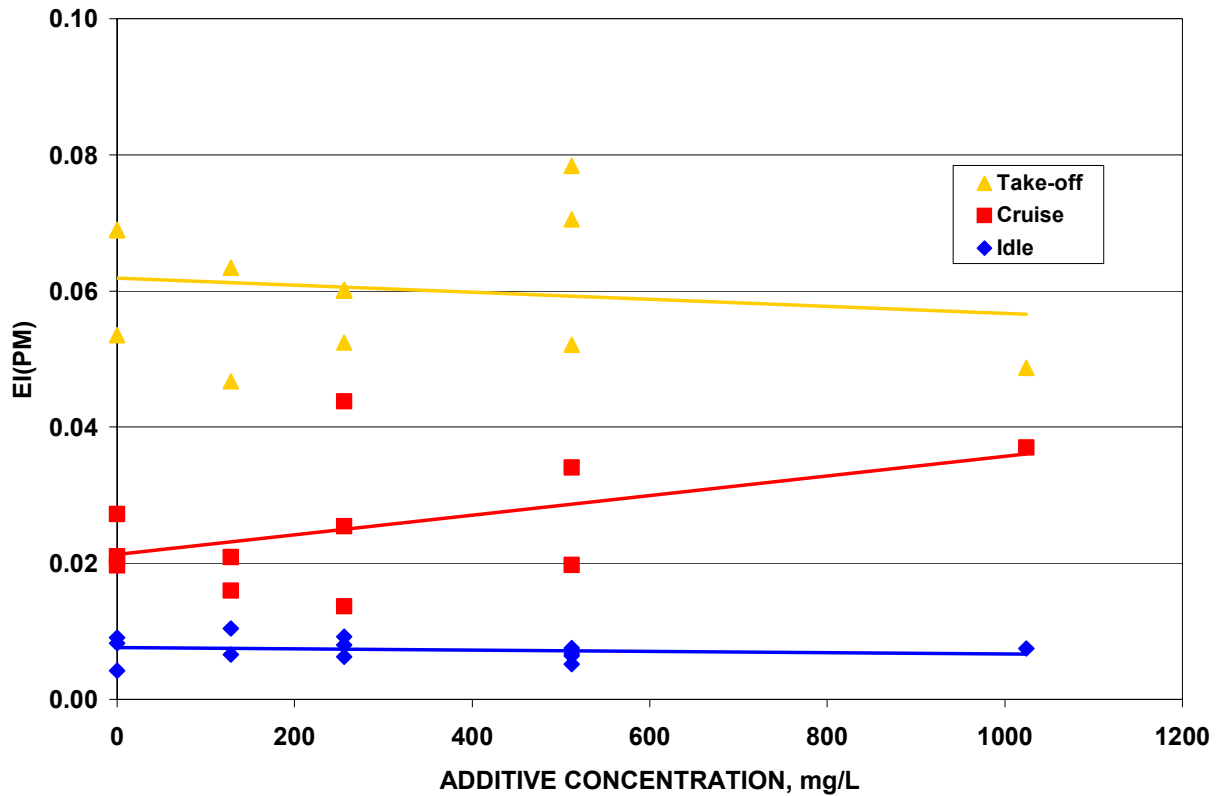


Figure 18. Effect of Additive Concentration on Exhaust Particulates: All Data

However, on the third day of the concentration tests at the takeoff condition, the flows were very stable and the fuel-air ratios calculated from the emissions were within 5% of the measured fuel-ratio for all of the data at varying additive concentration. The particulates data for these tests are presented separately in Figure 19. The data indicate a slight decrease in particulate concentration with increasing additive concentration. This does not seem to be a very significant reduction considering the large increase in additive concentration.

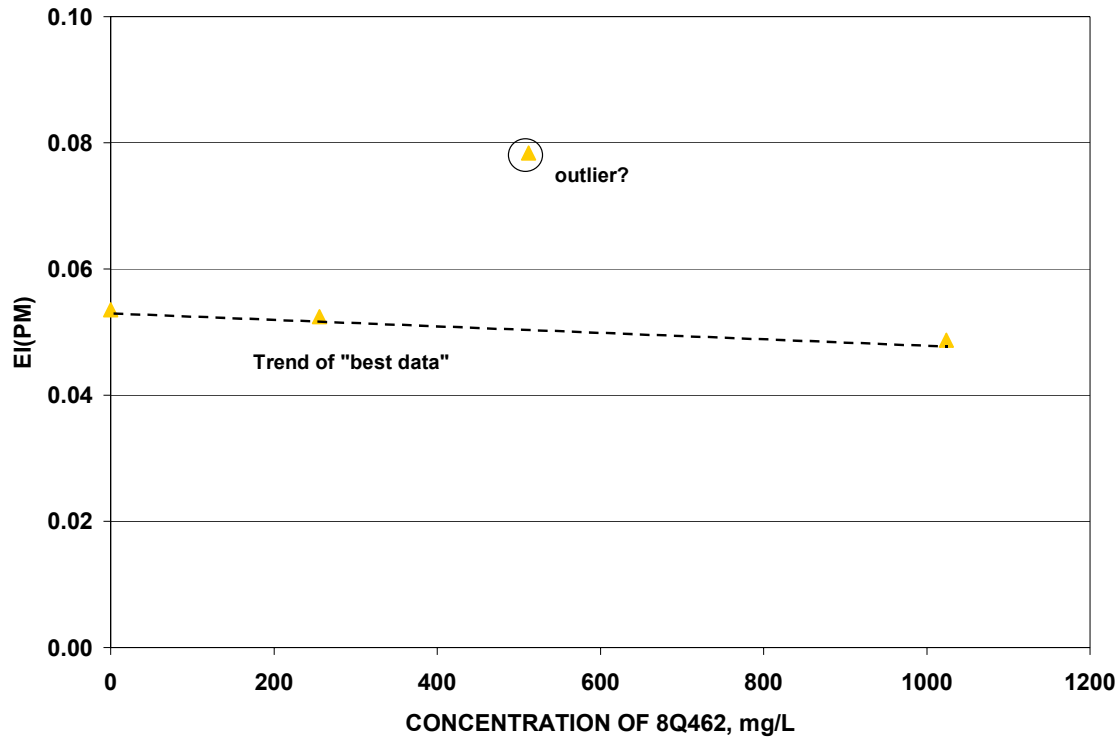


Figure 19. Effect of Additive Concentration on Exhaust Particulates: Best Data

5.6.3 Effect of Extended Testing Time

There has been a question of whether the additive, 8Q462, acts to reduce particulates immediately by chemical interference during the combustion process, or if it is a gradual clean-up of the combustor with time. To address this question, a five-hour test was conducted during which particulates were sampled several times. The results at the cruise and take-off conditions are presented in Figure 20. The operating conditions for these tests at the take-off condition were much more stable than for the cruise tests and agreement between the fuel-air ratio determinations was within 10% and are considered to be some of the best of the combustor data. Although a slight increase in particulate concentration with time is shown, it is likely that this is within the normal experimental variation. It is concluded that there was no significant reduction in particulates with time and therefore no clean-up action by the additive.

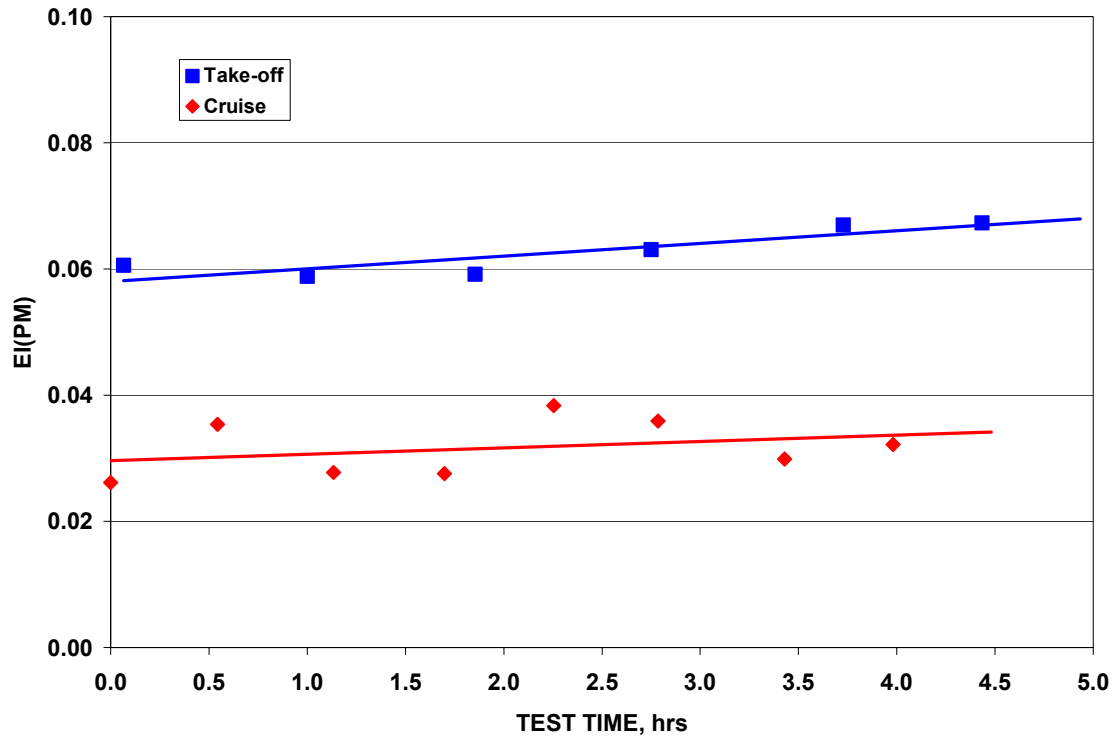


Figure 20. Particulates Data for Extended-Duration Combustor Test

5.6.4 Particle-Size Distribution

Flow samples were taken for particle-size distribution, PSD, during the time that the filter samples were being taken. Five consecutive samples were taken and analyzed. It was hoped that this would provide a more complete set of data than had been obtained during the engine tests since the combustor tests included particulate mass data at the take-off condition; data that could not be taken with the engine due to time constraints on operating the engine at the max power condition.

Unlike previous experience taking PSD data with the T700 combustor, the distributions were often very noisy, containing spurious peaks, as will be shown. Also, the scan-to-scan variations were much larger than previous experience. This has been attributed to the variations in the fuel flow, and hence fuel-air ratio, previously mentioned.

Figure 21 illustrates typical scatter in the data for a single scan; the data has been fitted with a log normal regression curve. Although much of the data falls very close to the curve, many sequential points alternate significantly above and below the line. Figure 22 presents the log normal regression curves for 5 consecutive scans taken about 2 minutes apart; these were for the same fuel at the same nominal flow conditions.

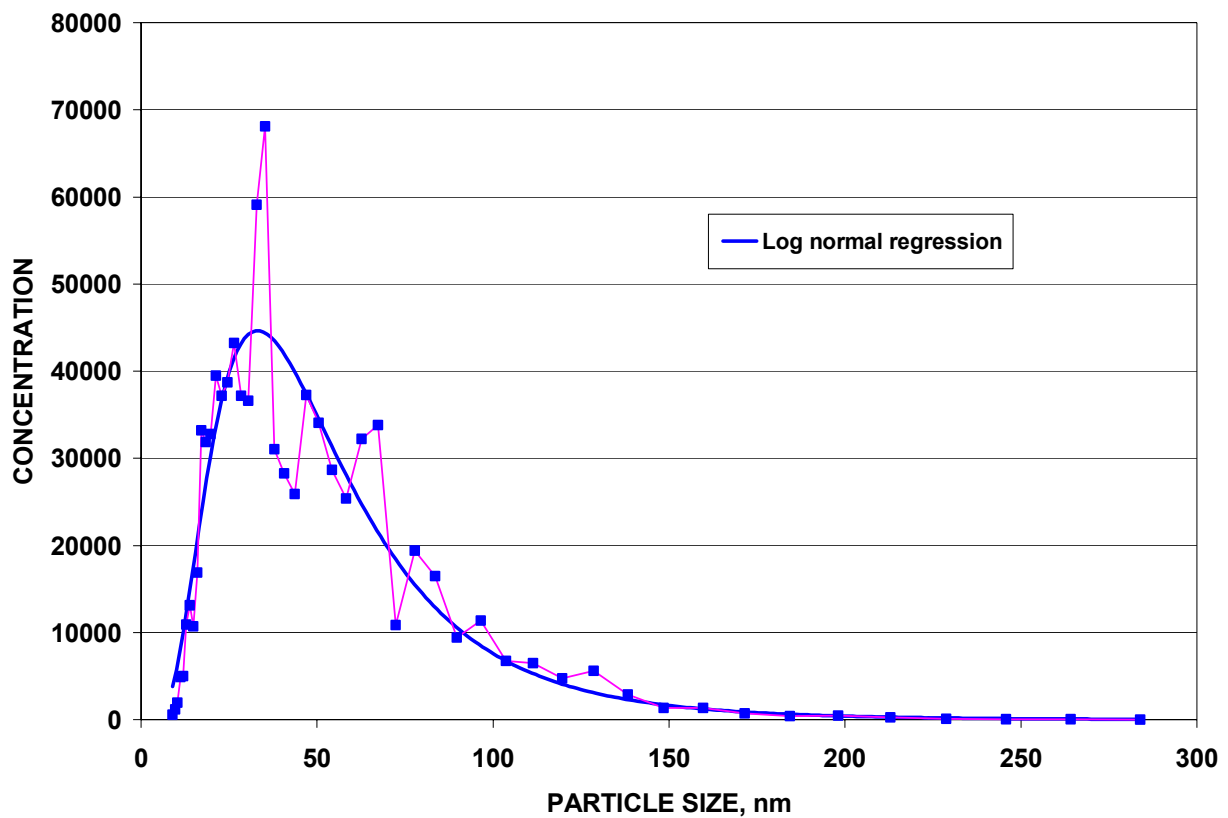


Figure 21. Typical Example of Particle-Size Distribution Data with Log Normal Regression

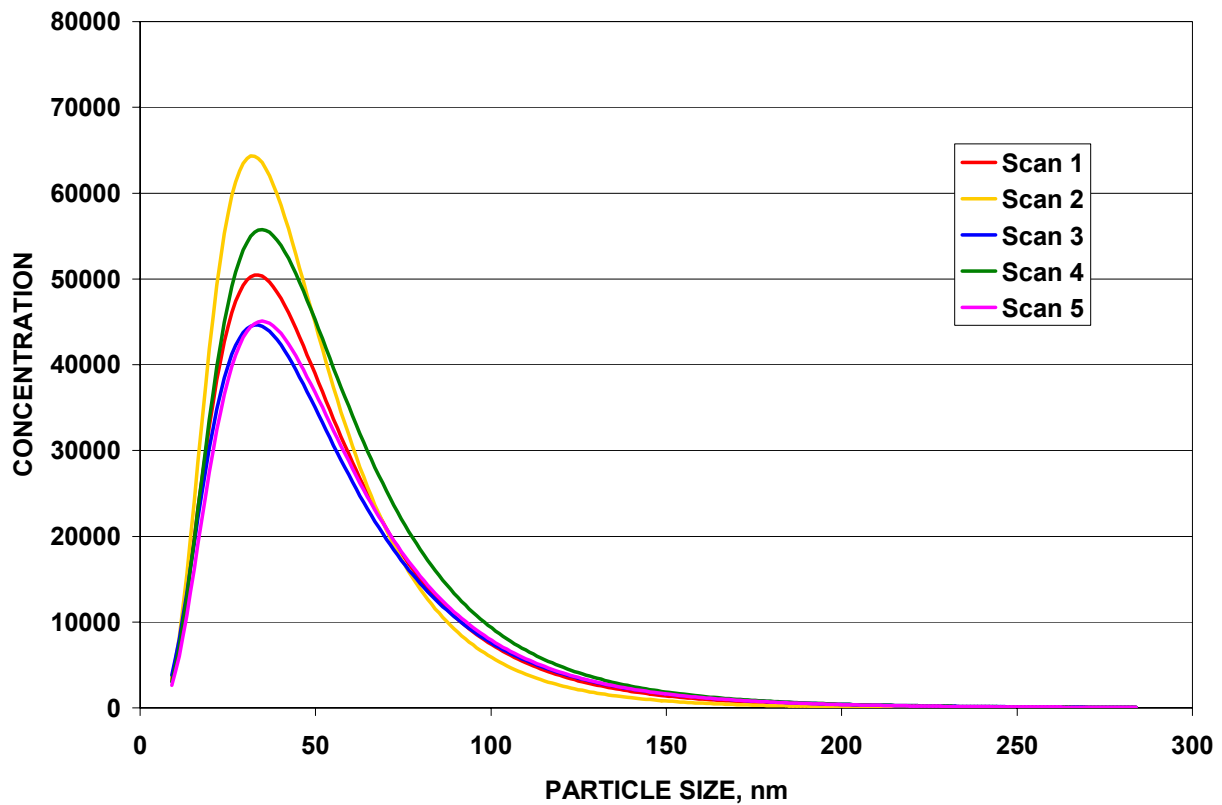


Figure 22. Consecutive Scans for Particle-Size Distribution

Figure 23 shows that it is possible to see significant differences among fuels, but the quality of the data is not sufficient to quantify the differences. These data are for the take-off power condition. On average, the F-76 with the additive is somewhat lower than without the additive, which is consistent with the engine data, but the scatter prevents any solid conclusions based on these data alone. The JP-5 and GTL fuels produced significantly fewer particulates than the F-76, which is consistent with both the engine and combustor filter data.

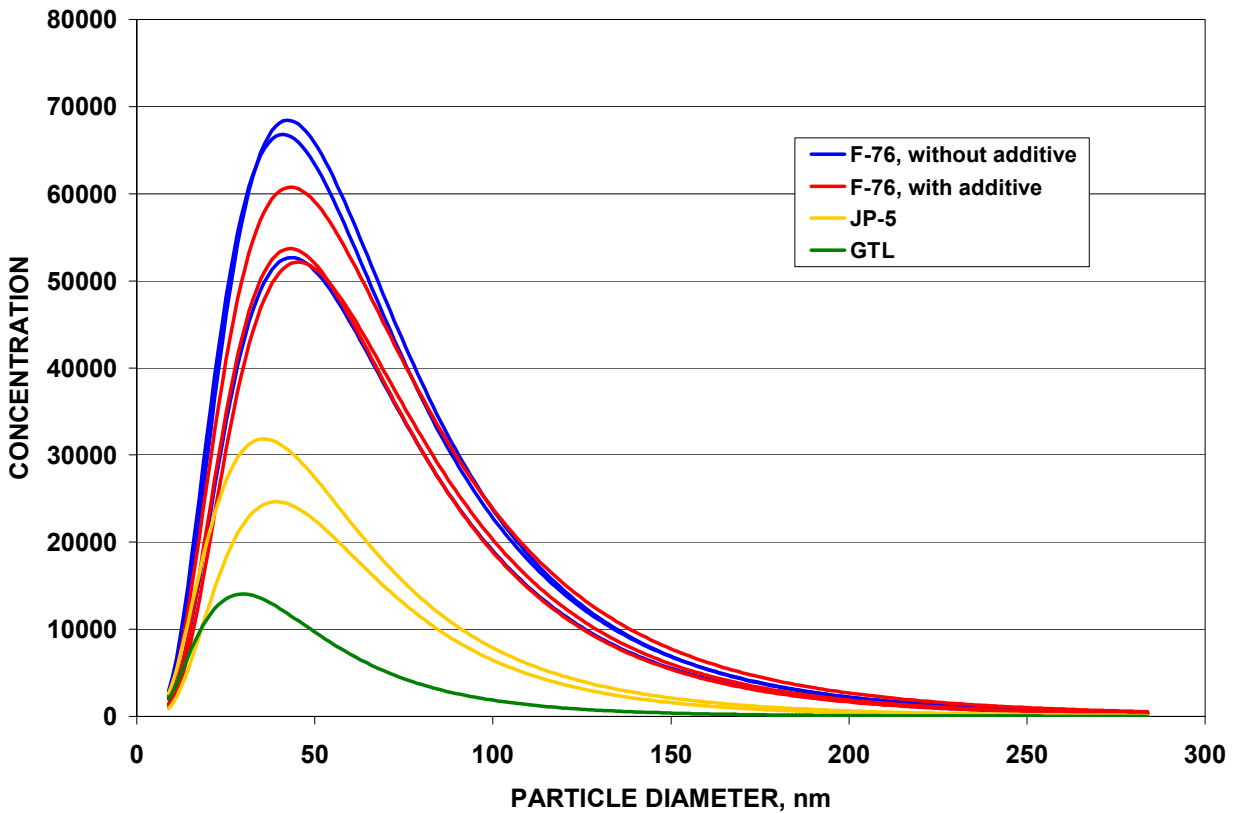


Figure 23. Fuel Effects on Particle Size Distribution at Take-Off Condition

At this point, it would take a considerable effort to work through the PSD data and weed out bad data in an attempt to be more quantitative. One could fit all of the scans with log normal regressions and eliminate obviously bad points. The regressions could then be averaged and re-examined. The magnitude of this effort was beyond the resources of this project. In previous combustor tests this was not necessary and such an effort was not included in estimating the level of effort. Given the state of the PSD data, it is doubtful that such an effort would be fruitful even if funded.

5.7 Problems

The basic problem with this project is thought to be caused by variations in the rate of fuel flow coming from drums stored outside the test cell. Any change in the fuel flow rate, however small, will result in a change in the heating rate within the combustor. This in turn will lead to fluctuations in the density of the gas and therefore the volume flow of air through the system for the same

combustor pressure. When the fuel flow and heating rate increase, the mass flow of air will decrease and vice versa. Thus, small changes in fuel flow rate can lead to larger changes in fuel-air ratio, which is a major factor in particulate formation. The combustor air pressure and temperature were very constant through a test, and very repeatable from test to test.

The variations in heating rate would have also caused spatial and temporal non-uniformities in the basic flow through the combustor. Since the gaseous emissions and particulates were only being sampled at a single point, this would be another cause of variations.

The variations were not noticeable in the initial tests at the idle condition, and those data were much more consistent as shown in Figure 6. The variations in fuel flow rate began when the weather got colder in combination with beginning the tests at the cruise condition, which had a much higher flow rate. For these tests, the fuel flow rates at cruise and takeoff conditions were higher than previously used because of the desire to match the operating conditions of the engine test.

The standard operating procedure has been to pressure the fuel drums to bring the fuel to the suction side of the high-pressure pump. Once the problem was noticed and studied, several approaches were attempted. Some appeared to work initially, but we were fooled by a few days of warmer weather which happen quite often in San Antonio in the winter months. The ideal solution would have been to put a boost pump on every fuel drum, but this was impractical. Eventually, a single boost pump was put in the fuel line downstream of the manifold that had a strong suction side and was better able to pull the fuel in. The success of this solution was seen in the more uniform fuel flows and agreement of fuel-air ratio in the latter part of the testing at the take-off condition.

It would seem reasonable to expect the problem would have been totally solved before continuing with the testing. However, the changeable weather provided a false sense of hope, and there was a tendency to be optimistic since the project was about six months behind schedule getting started due to a faulty data acquisition system.

The changeable weather was also the cause of another problem. A sudden heavy rainstorm came up one afternoon and caused a sudden drop in the pressure of the liquid nitrogen Dewar. This resulted

in a sudden drop in the coolant flow to the particulates probe and consequently and burned probe which had to be re-fabricated.

One problem that occurred in previous testing with the T700 combustor appears to have been fixed. The previous method of attachment of the combustor to the housing did not allow sufficient cooling at the aft skirt of the combustor. The ceramic used in that area to provide insulation would often crack and/or break off. Not only did the ceramic have to be replaced routinely, but also the bits and pieces would interfere with the particulate measurements. The new installation seems to have cured the problem, as there were no cooling problems even at the take-off condition.

5.8 Summary

On average, the particulate mass results agreed with the engine results with respect to power condition and gross fuel effects like hydrogen content. The scatter in the data was often greater than the contaminant and additive effects making quantitative assessments very tenuous. Copper contamination did not appear to cause an increase in particulates. There did appear to be a decrease in particulate concentration with increasing additive concentration, but if valid, it was small compared to the increase in additive concentration.

In extended duration tests of five hours, there was no evidence of a continued reduction in particulates that would be associated with combustor clean up. In fairness, it may be that the combustor was not “dirty”, in which case clean up would not be evident.

6. REFERENCES

1. Petroleum Quality Information System Aviation Fuel Data (PQIS), Defense Energy Support Center (DESC), Fort Belvoir, VA, 2002.
2. Effects of Spec·Aid™ 8Q462 on Particulate Emissions from a Gas Turbine Combustor, Final Report to Betz Dearborn, The Woodlands, TX, March 2002.